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PRODUCTIVITY CONVERGENCE ACROSS INDUSTRIES AND COUNTRIES: THE IMPORTANCE OF THEORY-BASED MEASUREMENT

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Cross-country studies of economic growth have been hampered by the scarcity of reliable data on productivity at the industry level; see Bernard and Jones [*American Economic Review*, 91 (4) (2001), 1168–1169] and Rogerson [*Journal of Political Economy*, 116 (2) (2008), 235–259]. We bring together literature on industry prices, human capital, and capital assets to construct industry-level productivity measures that are well grounded in neoclassical production theory. These theory-based measures differ widely from the crude measures commonly used in the literature. We use these to confirm and strengthen the finding of Bernard and Jones [*American Economic Review*, 86 (5) (1996), 1216–1238] that for advanced OECD countries, patterns of convergence across sectors have differed since 1970: whereas productivity in market services converged, there is no convergence in manufacturing. More detailed analysis confirms that patterns of convergence are highly industry-specific. There is no dominant convergence trend in sectoral productivity growth across advanced countries.

Keywords: Convergence, Economic Growth, Productivity Measurement, Sectoral Trends

1. INTRODUCTION

Comparative productivity levels are an important ingredient in cross-country studies of economic growth. Initially, such research was mainly focused on explaining patterns of convergence and divergence at the aggregate level.[1] More recently, studies on the differences in performance at the sectoral level (agriculture, manufacturing, and services) have appeared, motivated by the influential study by Bernard and Jones (1996), henceforth BJ. They found that across a set of selected

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OECD countries, convergence at the aggregate level does not necessarily imply convergence at the industry level. In particular, they found that during the period 1970–1987 manufacturing showed little evidence of productivity convergence, in contrast to the services sector, in which convergence was strong.

These findings have not been undisputed. Sørensen (2001) showed that the finding of nonconvergence in manufacturing depended heavily on the choice of a set of purchasing-power parities (PPPs) to convert national currencies into comparable units. BJ used one set of aggregate GDP PPPs to convert all sectoral variables. However, because sectoral prices do not move in tandem over time, the sectoral findings of BJ became highly sensitive to the choice of a base year for the aggregate PPPs. Typically manufacturing prices grow much more slowly than prices of services, and a common PPP would not capture this difference. In their reply, BJ conclude that "future research is needed to construct conversion factors appropriate to each sector and that research relying on international comparisons of sectoral productivity and income should proceed with caution until these conversion factors are available" [Bernard and Jones (2001, p. 1169)].

Since then, research relying on sectoral productivity comparisons has boomed. Productivity levels figure prominently in cross-country studies of technology spillovers, multisector growth, and dynamic models of trade.[2] However, the warning by Sørensen still lingers, as evidenced by the remark in Rogerson (2008) that "systematic sectoral accounts that permit cross-country comparisons of sectoral productivity have not yet been developed. Whereas aggregate productivity comparisons such as those provided by the Penn World Tables can be carried out using only prices for final goods and investment, one would also need international prices for all intermediate inputs to compute relative sectoral value-added productivities. Without accounts that explicitly address this issue, the numbers that one obtains from various exercises are not reliable" (p. 251).[3]

In this study we develop a new database of comparative productivity levels that directly confronts this criticism, called the *GGDC productivity level database*. It is based on a new set of PPPs for both output and intermediate inputs at a detailed industry level. In addition, novel measures of labor and capital inputs are used, which take account of differences in the composition of each input, such as different levels of skills or types of capital goods, such as information and communication technologies (ICT) and other assets. The basic methodology, grounded in neoclassical production theory, has a long history but has never been comprehensively applied in a large cross-country setting, mainly due to a lack of suitable data.[4] As an alternative, many studies have relied upon crude measures of input, output, and productivity. We show that the theory-based measures from the new database differ widely from the crude measures commonly used in the literature, justifying the warnings mentioned above.

The new database offers plenty of opportunities for new analysis, and we illustrate this with a sigma-convergence analysis in the tradition of Bernard and Jones (1996). We find that their main message was basically right: patterns of convergence in a set of advanced OECD countries differ considerably across sectors. Since the 1970s, we find a process of steady convergence in market services. In contrast, there is little evidence for convergence in manufacturing or other goods-producing industries, and even some suggestion of divergence since the mid-1990s. Moreover, when we analyze convergence at a more detailed industry level using a dataset of 24 industries, we find that patterns of convergence and divergence since 1980 are very different and far from homogenous even within industry groups such as market services.

This study is related to various strands of literature that have highlighted and addressed the problems of crude productivity measurement, albeit only in a piecemeal fashion. It is akin to work by Biesebroeck (2007) and Sørensen and Schjerning (2009), who redo the convergence analysis of Bernard and Jones (1996) by applying sectoral PPPs. However, they do not account for intermediate input prices, and they ignore differences in the composition of capital and labor inputs. On the other hand, de la Fuente and Doménech (2006) and Cohen and Soto (2007) provide growth and convergence studies based on detailed measures of labor input, but only for the aggregate economy level. Caselli and Wilson (2004), Jorgenson and Vu (2005), and Timmer and van Ark (2005) provide countrywide comparisons of productivity allowing for different types of capital, in particular ICT-capital, whereas Hsieh and Klenow (2007) highlight the importance of differences in relative prices of various asset types. All these studies emphasize the empirical importance of using detailed measures of prices and quantities of output and inputs. This study, though, is the first to bring together these various strands of the literature in a unified framework to measure productivity levels. Based on this, we provide the first comprehensive set of comparative productivity levels at the industry level for a large set of OECD countries.

The rest of the paper is organized as follows. In Section 2 we outline the methodology for comparing levels of output, input, and productivity across countries. In Section 3 we describe the data sources we use to implement this methodology. Section 4 compares different productivity level estimates for our benchmark year, 1997, and traces these differences to refinements in measurement of inputs and output. Section 5 then reexamines the evidence for sectoral convergence patterns along the lines of Bernard and Jones (1996), and Section 6 concludes.

2. METHODOLOGY

In this section we present our methodology for comparing levels of output, input, and productivity across countries, so-called level accounting.[5] This approach has a long history, dating back to the seminal article by Jorgenson and Griliches (1967) and extended in a range of studies by Jorgenson and various collaborators [see Jorgenson (1995a, 1995b)]. It was further grounded in economic theory by Diewert (1976), Caves et al. (1982b), and Diewert and Morrison (1986). As we are trying to construct a consistent set of productivity measures for a large number of countries and industries at the same time, various choices have to be made concerning not only the use of particular index number formulae, but also their actual implementation. In this section the basic methodology is laid out, which consists of two steps. In the first step, PPPs for output, capital, labor, and intermediate inputs for 29 industries are derived based on data for 45 subindustries. This is done with the price variant of the multilateral index number approach advocated by Caves et al. (1982a), also known as the CCD method. These PPPs are used to implicitly derive quantities of all inputs (capital, labor, and intermediate inputs) and output. In the second step, productivity comparisons are made for each industry on the basis of input and output quantities in a bilateral Törnqvist model, following Diewert (1976) and Jorgenson and Nishimizu (1978). This approach is also known as primal-level accounting.[6] In this section we first outline our basic methodology for measuring productivity, followed by our approach to deriving PPPs for outputs and inputs. Our general notation is as follows. Variable *V* indicates values in current national prices, *PPP* indicates a relative price index across two countries, and *Q* indicates a quantity index. Superscripts indicate the type of output or inputs, and subscripts indicate industry *j*, country *c*, and time *t*.

In this paper, we only outline the methodology for measures of multifactor productivity (MFP) based on value added, taking into account both labor and capital services as inputs.[7] We assume that production in industry *j* in a country *c* takes place according to the production function *F:*

$$Q^{VA}_{c,j,t} = F\left(Q^{K}_{c,j,t}, Q^{L}_{c,j,t}, T\right), \tag{1}$$

with Q^{VA}, Q^{K}, and Q^{L} quantity indices of value added, capital services, and labor services, respectively, and *T* indicating time. Following Jorgenson and Nishimizu (1978), we define a translog index of difference in multifactor productivity. Under the necessary conditions for producer equilibrium in each country, this index is defined for a country *c* in industry *j* as follows:[8]

$$\ln \mathrm{MFP}_{c,j} = \ln \frac{Q^{VA}_{c,j}}{Q^{VA}_{US,j}} - \bar{w}^{K}_{j} \ln \frac{Q^{K}_{c,j}}{Q^{K}_{US,j}} - \bar{w}^{L}_{j} \ln \frac{Q^{L}_{c,j}}{Q^{L}_{US,j}}. \tag{2}$$

The weights are defined as the share of each factor input in value added averaged over the two countries. $\bar{w}^{K}_{j}$ is the share of capital services in value added averaged over the two countries: $\bar{w}^{K}_{j} = w^{K}_{c,j} + w^{K}_{US,j}$ with $w^{K}_{c,j} = V^{K}_{c,j} \big/ V^{VA}_{c,j}$ and V^{K}_{c} the nominal value of capital compensation in country *c*, and similarly for labor. We assume constant returns to scale such that $\bar{w}^{K}_{j} + \bar{w}^{L}_{j} = 1$.

Our models of production are bilateral and involve comparisons of a country *c* with the United States as base. We chose the United States as the base country because these comparisons generally generate the highest interest, the United States being the overall productivity leader. Alternative bilateral comparisons with other countries as the base can be made using the same approach by simply replacing the United States with another base country in the formulas given above.[9] The formulas indicate that comparable volume measures of output and inputs for the countries are needed. When a single output or input is being compared, physical measures, such as number of cars or hours worked, are possible. However, comparisons at the industry or aggregate level require quantity indices to be calculated implicitly by the ratio of the nominal values and the relevant price indices. This is usually done with a purchasing power parity (PPP) that indicates the relative price of output or input in one country relative to another country. A volume index of labor services is given by

$$Q^L_{c,j} = \frac{V^L_{c,j}}{\mathrm{PPP}^L_{c,j}}, \tag{3}$$

with $V^L_{c,j}$ the nominal value of labor compensation in country c (at current national prices) and $\mathrm{PPP}^L_{c,j}$ the price of labor services in country c relative to the United States. And similarly for aggregate capital input in country c,

$$Q^K_{c,j} = \frac{V^K_{c,j}}{\mathrm{PPP}^K_{c,j}}, \tag{4}$$

with $V^K_{c,j}$ the nominal value of capital compensation in country c and $\mathrm{PPP}^K_{c,j}$ the relative price of capital services in country c.[10] Finally, value-added volume in country c is given by

$$Q^{VA}_{c,j} = \frac{V^{VA}_{c,j}}{\mathrm{PPP}^{VA}_{c,j}}. \tag{5}$$

The PPPs for outputs and inputs required in (3)–(5) are derived on the basis of detailed sets of output and input prices.[11] Prices are aggregated using the multilateral translog price indices introduced by Caves et al. (1982a) (CCD index). Basically, in this methodology, one creates an artificial country by averaging over all countries in the data set and uses this constructed country as a bridge when making binary comparisons between two countries. This creates so-called transitive PPPs that are base-country independent. As with our MFP indices, the PPPs are normalized with the United States as 1.

Labor and capital volume indices grounded in production theory should take into account the composition of each factor input, such as different levels of skills or types of capital goods (in particular, ICT versus non-ICT assets). For labor, this can be achieved by deflation with an appropriate PPP based on relative wages of each labor type l as follows:

$$\ln \mathrm{PPP}^L_{c,j} = \sum_l \bar{v}^l_{c,j} \left\lfloor \ln \mathrm{PPP}^l_{c,j} - \overline{\ln \mathrm{PPP}^l_j} \right\rfloor, \tag{6}$$

where the bar in the last term indicates a geometric average over all countries, indexed by $c = 1, \ldots, N$ and N is the number of countries such that $\overline{\ln \mathrm{PPP}^l_j} = 1/N \sum_c \ln \mathrm{PPP}^l_{c,j}$. And $\bar{v}^l_{c,j}$ is the average weight of labor type l, defined as $\bar{v}^l_{c,j} = \frac{1}{2}[v^l_{c,j} + \Sigma_c(v^l_{c,j}/N)]$, with $v^l_{c,j}$ the share of labor type l in total labor compensation in country c: $v^l_{c,j} = V^l_{c,j}/V^L_{c,j}$. The PPP for each labor type is derived on the basis of relative wages as described in Section 3.

The derivation of an appropriate capital PPP is basically similar to that of a labor PPP. Suppose one has a PPP for each capital asset type k; then the aggregate capital PPP is given by

$$\ln \mathrm{PPP}^K_{c,j} = \sum_k \bar{v}^k_{c,j} \left\lfloor \ln \mathrm{PPP}^k_{c,j} - \overline{\ln \mathrm{PPP}^k_j} \right\rfloor. \quad \textbf{(7)}$$

For the deflation of value added, a double deflation procedure is used based on separate PPPs for gross output and intermediate inputs as required [Jorgenson et al. (1987)]. We follow a CCD-like approach by taking a geometric mean of all possible binary Törnqvist indices for a particular country c. First, we calculate the binary value-added PPP for each country pair (c, d) as follows:

$$\left[\ln \mathrm{PPP}^{VA}_{c,j} - \ln \mathrm{PPP}^{VA}_{d,j}\right] = \frac{1}{1-\bar{v}^{II}_{c,d,j}} \left[\left(\ln \mathrm{PPP}^Y_{c,j} - \ln \mathrm{PPP}^Y_{d,j}\right) - \bar{v}^{II}_{c,d,j}\left(\ln \mathrm{PPP}^{II}_{c,j} - \ln \mathrm{PPP}^{II}_{d,j}\right)\right]. \quad \textbf{(8)}$$

The weight $\bar{v}^{II}_{c,d,j}$ is the share of intermediate inputs in gross output, averaged over the two countries. $\mathrm{PPP}^Y_{c,j}$ is the multilateral index for output and derived analogously to the derivation of labor PPPs, but now using shares of output types in total output value as weights, and similarly for $\mathrm{PPP}^{II}_{c,j}$, which is the multilateral index for intermediate input. Finally, a G-EKS procedure is applied to multilateralize the set of value-added binaries given in (8), as in Caves et al. (1982a).

Equations (2) to (8) provide the system of equations used to derive MFP measures consistent with neoclassical production theory. In Section 4 a comparison will be made with cruder measures of MFP, which do not take into account detailed measures of various labor and capital types, and neglect differences in sectoral output and input prices. In particular, many studies use GDP PPPs to deflate industry-level outputs and inputs:

$$\mathrm{PPP}^{VA}_{c,j} = \mathrm{PPP}^{\mathrm{GDP}}_c. \quad \textbf{(9)}$$

As noted in the literature, this approach ignores the difference in prices across various industries and the differences in prices of intermediate inputs and outputs [Sørensen (2001); Rogerson (2008)]. This can easily be seen when our data-intensive measure given in (8) is compared with (9).

When it comes to measuring labor input volumes, some studies only measure the relative numbers of persons engaged, whereas others also account for differences in average hours worked across countries. Implicitly, these studies use the following

PPP for labor:

$$\text{PPP}^{L}_{c,j} = \left(\frac{V^{L}_{c,j}}{\tilde{Q}^{L}_{c,j}}\right) \Bigg/ \left(\frac{V^{L}_{\text{US},j}}{\tilde{Q}^{L}_{\text{US},j}}\right), \tag{10}$$

with $\tilde{Q}^{L}_{c,j}$ the quantity of aggregate labor input in industry j and country c, directly measured as total number of workers, or total hours worked. In contrast to our data-intensive measure given in (6), this measure does not account for differences in the composition of the workforce in different countries.

Finally, as a measure of capital input volumes, most studies use a measure of the relative capital stock. Typically, as data on capital stocks is given in national prices, a GDP PPP is used to make them comparable across countries, as follows:

$$\text{PPP}^{K}_{c,j} = \text{PPP}^{\text{GDP}}_{c}\left(\frac{V^{K}_{c,j}}{\tilde{Q}^{K}_{c,j}}\right) \Bigg/ \left(\frac{V^{K}_{\text{US},j}}{\tilde{Q}^{K}_{\text{US},j}}\right), \tag{11}$$

with $\tilde{Q}^{K}_{c,j}$ the quantity of aggregate capital in industry j and country c, directly measured as the capital stock summed over all asset types. Consequently, this crude measure of capital does not take into account differences in investment prices, nor differences in the composition of capital. Our detailed measure in (7) above is based on a comparison of capital service levels, accounting for asset heterogeneity and investment PPPs.

In our empirical analysis, both the data-intensive and the crude measures of MFP-levels are extrapolated over time. The level comparisons are made for the year 1997. Growth rates of MFP are applied to generate series of MFP levels over the period 1970–2005. For the data-intensive measure, MFP growth rates (value added–based) are taken from the *EU KLEMS database*, March 2008, which includes adjustments for changes in the composition of labor and capital over time. The time series of MFP growth used to extrapolate the crude measure of MFP do not take this into account. They are calculated by subtracting the weighted growth in persons engaged and growth of the capital stock from growth in value-added volumes. The weights are the same as for the data-intensive measure. These series are also taken from the EU KLEMS database, March 2008.

3. DATA

In this study we use a combination of the GGDC productivity level database and the EU KLEMS growth accounting database. The first database provides productivity level comparisons for twenty OECD countries at a detailed industry level using the methodology outlined in Section 2. These comparisons are only made for one particular benchmark year, 1997. The EU KLEMS database is used to extrapolate this benchmark through time from 1970 to 2005. This is done at a detailed industry level. The list of industries is given in Table A.1. The EU KLEMS database has been extensively described elsewhere [see O'Mahony and Timmer (2009)]. Here we provide a short discussion of the underlying sources of the GGDC Productivity Level database.[12] All databases are available at www.ggdc.net.

This database is based on two main sets of data: a set of national input–output tables for the nominal values of output and inputs, and a set of PPPs for deflation. Input–output tables are not available for all countries in a common benchmark year, and we used supply and use tables to construct such a benchmark year. The starting point of our analysis is the national supply and use table for each country, valued in national currency for 1997. Eurostat makes these tables available for the European countries on a common industry classification and at a sufficient level of industry detail for the purpose of this study. For non-European countries these tables are obtained from the national statistical offices. They had to be adjusted to the European industry classification.

The value-added block of the tables only distinguishes two primary factors, namely capital and labor, so further disaggregation of these factor inputs is required. We use the labor and capital compensation as given in the EU KLEMS database, in which a correction is made for the labor income of the self-employed. Total hours worked and wages for each of the 18 labor types are taken from the EU KLEMS database and extended to 30 types by incorporating more detailed educational attainment data. Capital compensation is split into three ICT assets (computers, communication equipment, and software) and five non-ICT assets (residential structures, nonresidential structures, transport equipment, other non-ICT equipment, and other assets). The share of each asset in total compensation is based on capital rental prices using the ex ante approach. We multiply the asset- and industry-specific rental prices with the capital stock taken from the capital input files from the EU KLEMS database to derive the ex ante capital compensation by asset.[13]

Output PPPs are defined from the producer's point of view and are at basic prices. These PPPs have been constructed partly using unit value ratios for agricultural, mining, and manufacturing products and transport and communication services. For the other market industries, PPPs are based on specified expenditure prices from Eurostat and the OECD, which were adjusted to industry level by using relative transport and distribution margins and adjusting for differences in relative tax rates.[14] PPPs have been made transitive by applying the multilateral EKS procedure for a set of 30 countries.[15] Intermediate input PPPs reflect the costs of acquiring intermediate deliveries and match the price concept used in the input–output tables, hence at basic prices plus net taxes. The data problems of obtaining input PPPs for individual industries are larger than those for output PPPs. There is often no input price parallel to the output PPPs. Business statistics surveys and productivity censuses provide little, or no, information on quantities and values of inputs in manufacturing, and for nonmanufacturing industries the information is largely absent. Moreover, PPPs from the expenditure side by definition do not reflect prices of intermediate inputs, as they cover only final expenditure categories. In this study we use output PPPs as a proxy for relative intermediate input prices under the assumption that the basic price of a good is independent of its use. That is, we use the same gross output PPP of an industry to deflate all intermediate delivers from this industry to other industries. The aggregate intermediate input PPP for a particular industry can be derived by weighting intermediate inputs at the output PPP from the delivering industries. Imported goods are separately identified and exchange rates are used as conversion factors for imports.

PPPs for labor inputs are derived by dividing a country's wage rate by the corresponding U.S. wage rate. This must be done at a detailed level of aggregation as characteristics of workers vary greatly across countries; see, for example, de la Fuente and Doménech (2006). For example, the share of college-educated workers in the United States is typically (much) higher than that in the European countries. By having a detailed breakdown into various labor types, we try to minimize problems of composition in the determination of relative wages. Labor input is cross classified by type of education (five types), age (three types), and sex into thirty groups. For each group in each industry, wages per hour worked are taken from the EU KLEMS database. They include all costs incurred by the producers in employment of labor, including taxes levied, health cost payments, other types of insurance, and contributions to retirement paid by the employer and financial benefits.

Capital PPPs give the relative price of the use of a unit of capital in two countries from the purchasers' perspective. To obtain relative prices for capital input, we follow Jorgenson and Nishimizu (1978). Under the assumption that the relative efficiency of new capital goods is the same in both countries, the relative rental price of an asset k between country c and the base country, the United States, (PPP_t^K) is calculated as

$$\mathrm{PPP}_t^K = \mathrm{PPP}_t^I \frac{p_{t,c}^K / p_{t,c}^I}{p_{t,\mathrm{US}}^K / p_{t,\mathrm{US}}^I}, \tag{12}$$

with lower-case p indicating prices, PPP_t^I the relative current investment price of asset k between country c and the United States, and p_t^K the cost of capital as defined below. This definition indicates that the relative rental price of a unit of capital between two countries depends on the relative investment price and the user cost of capital input. In the absence of taxation the familiar cost-of-capital equation for asset type k is given by

$$p_{t,c}^K = p_{t-1}^I r_t + \delta p_t^I - \left[p_t^I - p_{t-1}^I\right]. \tag{13}$$

This formula shows that the user cost is determined by the nominal rate of return (r), the rate of economic depreciation (δ), and the asset-specific capital gains. This is done for each asset type k in each industry j, using asset–industry–specific depreciation rates and investment prices.[16]

4. PRODUCTIVITY LEVELS: CRUDE VERSUS DATA-INTENSIVE

The preceding discussion has demonstrated that a large amount of data is needed to get close to the theoretical concept of productivity based on neoclassical production theory. Detailed information about the composition and relative prices of labor and capital is needed to get an accurate comparison of input across countries, and industry-specific output prices are needed for an accurate comparison of output. But an important question is whether all these refinements matter in practice or whether a cruder measure that is easier to implement would give qualitatively similar results. To examine this, we first look at comparative measures of inputs and outputs in detail in Tables 1 to 3, and next compare a number of alternative productivity level estimates based on varying data intensity in Table 4.

In Table 1 we present value-added PPPs for various sectors in the economy as a ratio of the overall GDP PPP. The ratios are given for three sectors: manufacturing, other goods and market services.[17] Most studies rely on GDP PPPs for conversion of sectoral output and as discussed in the Introduction, this has generally been seen as a major weakness of current convergence studies. The value-added PPPs have been derived by separate deflation of output and intermediate inputs as in equation (8). As shown in the table, the ratio of sectoral value added to GDP PPP can vary between 75% and more than 200%.[18] Importantly, the table shows that the ratio is not stable across sectors, indicating large differences in relative sectoral prices, confirming the findings by Biesebroeck (2007) and Sørensen and Schjerning (2009). For example, the relative production price of other goods in Japan is much higher than the relative price for manufacturing. This is mainly due to the high output prices in the agricultural sector, which is famous for its weak competitiveness and strong import protection [van Ark and Pilat (1993)]. The use of an overall GDP PPP would greatly overestimate productivity levels in this sector. On balance, the VA PPPs for manufacturing differ about 16% from the GDP PPP across our set of countries.[19] This directly translates into a 16% difference in measures of productivity levels. For market services the difference is comparable (15%), whereas for other goods it is even larger (32%).

Next we look at data-intensive measures of labor and capital input. To ease exposition, we only present results for the aggregate market economy, though a similar comparison could be made for each of the detailed industries in our dataset. Table 2 presents our measures of labor services input per worker compared to the United States. The most straightforward measure of labor input compares the number of persons engaged, but this popular measure neglects variation in the average number of hours worked and the composition of the workforce, as discussed in Section 2, equations (3), (6), and (10). As shown in the first column, average annual hours worked vary considerably across countries, between 1,474 hours in Belgium and 2,111 hours in Hungary.[20] Our measure of labor services also adjusts for differences in educational attainment of the labor force. The difference in skill levels across OECD countries is illustrated in the second column, which provides the share of highly skilled workers in employment.[21] Apart from Finland,

TABLE 1. Value-added PPPs for various sectors (as ratios of GDP PPP), 1997

	Manu-facturing	Other goods	Market services
Australia	1.42	0.75	1.12
Austria	1.47	1.29	1.32
Belgium	1.03	1.39	1.16
Czech Republic	1.20	1.21	1.42
Denmark	1.32	1.33	0.93
Finland	1.02	0.85	1.08
France	1.10	1.52	1.16
Germany	1.06	1.53	1.02
Hungary	1.06	1.55	1.07
Ireland	1.32	1.38	1.11
Italy	0.86	1.25	1.31
Japan	0.98	2.17	1.37
Luxembourg	1.18	1.85	0.79
Netherlands	1.20	1.58	0.96
Portugal	1.36	1.22	1.02
Slovenia	1.14	1.50	1.34
Spain	1.22	1.30	1.17
Sweden	1.12	1.08	1.09
United Kingdom	1.17	1.34	1.11
United States	1.00	1.00	1.00

Notes: PPPs for value added in various sectors divided by the GDP PPP. See Table 5 for definitions of the sectors.
Source: See Appendix Table A.1.

the United States appears to have the largest share of highly skilled workers, as also found by de la Fuente and Doménech (2006) and Cohen and Soto (2007). However, focusing only on workers with university education is potentially misleading, as it ignores differences in lower levels of education. For example, Germany has a comparatively large share of workers in vocational education categories, whose skills are highly valued in the labor market, as reflected in relatively high skill premia. Such a category of workers is not to be found in the United States. Furthermore, labor force characteristics such as age and sex are also relevant as indicators of work experience. Our detailed measures correct for this as well. The final column of Table 2 shows the amount of labor services per worker, which combines the effects of differences in hours worked and compositional differences across countries. Except for Hungary, all countries have lower inputs of labor services per worker than the United States. For countries such as Belgium, Denmark, and the Netherlands, this is mainly due to lower working hours, whereas

TABLE 2. Measures of labor input, 1997, market economies

	Average hours worked	Share of highly skilled workers (%)	Labor services per worker (U.S. = 1)
Australia	1,862	11	0.87
Austria	1,659	6	0.77
Belgium	1,474	11	0.75
Czech Republic	2,049	8	0.96
Denmark	1,537	5	0.68
Finland	1,842	27	0.86
France	1,745	9	0.90
Germany	1,526	6	0.77
Hungary	2,111	10	1.12
Ireland	2,023	9	0.97
Italy	1,968	5	0.91
Japan	1,837	19	0.97
Luxembourg	1,647	12	0.86
Netherlands	1,486	7	0.75
Portugal	1,912	5	0.62
Slovenia	1,897	10	0.85
Spain	1,768	10	0.83
Sweden	1,740	9	0.90
United Kingdom	1,797	11	0.86
United States	1,848	24	1.00

Source: GGDC productivity level database [Inklaar and Timmer (2008)].

for countries such as the Czech Republic, Portugal, and Slovenia, differences in labor composition are most important.

Table 3 looks at a crude and our data-intensive measure of capital input. The first column is based on comparisons of aggregate capital stock, as in equation (11), discussed in Section 2. The drawback of this measure is that it does not take into account differences in investment prices nor the composition of the capital stock. Both issues are empirically important, as indicated by Caselli and Wilson (2004) and Hsieh and Klenow (2007). Whereas in the past capital stocks provided a good proxy for capital input levels, this is no longer the case in the ICT era. Jorgenson and Vu (2005) and Timmer and van Ark (2005) highlighted the diverging trends in the use of ICT capital and its impact on comparative productivity levels. This is illustrated in column (2), which presents the share of ICT assets in total capital compensation. This share is more than 20% in Denmark, Sweden, the United Kingdom, and the United States, but less than 11% in the Czech Republic, Ireland, Italy, and Portugal. Comparisons based on detailed measures of capital according to equation (7) are given in the final column. As almost all countries use less ICT than the United States, relative capital input services are lower than relative levels of stocks. In general, the smaller the share of ICT, the bigger the difference between the crude and data-intensive measures.

TABLE 3. Measures of capital input per hour worked, 1997, market economies

	Capital stock per hour worked (U.S. = 1)	ICT share in total capital compensation	Capital services per hour worked (U.S. = 1)
Australia	1.31	16.3	1.03
Austria	1.44	13.4	1.12
Belgium	1.95	18.0	1.59
Czech Republic	0.93	8.3	0.45
Denmark	1.40	21.8	1.24
Finland	1.23	17.5	1.17
France	1.15	16.6	0.90
Germany	1.18	18.4	1.06
Hungary	0.95	12.9	0.47
Ireland	0.83	10.0	0.58
Italy	1.25	10.7	1.06
Japan	1.18	19.4	1.19
Luxembourg	1.49	21.6	1.32
Netherlands	1.24	17.2	1.03
Portugal	0.49	10.9	0.40
Slovenia	0.78	26.9	0.49
Spain	1.01	17.0	0.69
Sweden	1.18	23.8	1.09
United Kingdom	0.84	22.0	0.75
United States	1.00	26.8	1.00

Sources: Capital stock based on aggregate stocks in national currencies from EU KLEMS database [O'Mahony and Timmer (2009)], converted with GDP PPPs from the OECD (2002). Share of ICT in total capital compensation and capital services based on GGDC productivity level database [Inklaar and Timmer (2008)].

In addition, relative prices between equipment and other capital assets such as buildings and structures are known to differ, as the former are mostly imported, whereas the latter are domestically constructed. The latter depend largely on local wages, and its PPP is usually close to the GDP PPP (Hsieh and Klenow, 2007). In contrast, PPPs for equipment are closely related to exchange rates. For countries in which exchange rates are much higher than the overall GDP PPP, the crude capital input measures as given in equation (11) will be overestimated. This is the case, for example, for the Czech Republic, Hungary, and Slovenia. All in all, for these countries, data-intensive measures of capital input can be as low as only half of the crude measures. But also, for other countries, differences can be sizeable. For example, for France, we find a 25-percentage-point difference.

TABLE 4. Measures of 1997 market economy MFP levels, United States = 1

	MFP1	MFP2	MFP3	MFP4
Australia	0.75	0.82	0.75	0.81
Austria	0.72	0.86	0.63	0.68
Belgium	0.87	1.05	0.90	0.96
Czech Republic	0.45	0.46	0.37	0.48
Denmark	0.75	0.97	0.90	0.94
Finland	0.76	0.84	0.82	0.84
France	0.88	0.94	0.78	0.84
Germany	0.82	0.98	0.90	0.93
Hungary	0.44	0.41	0.36	0.47
Ireland	0.99	1.01	0.87	0.99
Italy	0.82	0.88	0.74	0.78
Japan	0.69	0.71	0.52	0.52
Luxembourg	1.04	1.14	1.17	1.22
Netherlands	0.79	0.97	0.89	0.94
Portugal	0.56	0.77	0.68	0.74
Slovenia	0.50	0.56	0.43	0.49
Spain	0.79	0.89	0.75	0.85
Sweden	0.84	0.90	0.82	0.84
United Kingdom	0.83	0.92	0.78	0.81
United States	1.00	1.00	1.00	1.00
		Measurement alternatives		
PPP	GDP	GDP	VA	VA
Labor	Persons	Hours by type	Hours by type	Hours by type
Capital	Stock	Stock	Stock	Services by type

Source: Authors' calculations based on GGDC productivity level database [Inklaar and Timmer (2008)].

So far we have only discussed measures for the market economy as a whole. As shown by Stiroh (2002), there is wide dispersion of ICT intensity across sectors in an economy with generally high levels of ICT -investment in market services sectors such as finance and business services, communication, and transportation. This cross-industry pattern is also found in our dataset: the cross-country level differences found for the market economy are generally also reflected at lower industry levels [see Inklaar and Timmer (2008)].

Each adjustment to output and input volumes discussed above has a direct impact on the measurement of MFP. Table 4 brings the previous tables together by comparing four alternative productivity level estimates using increasingly data-intensive methods when moving from left to right. So the first column shows a crude measure, where GDP PPPs are used to convert output to a common currency, the number of persons engaged is used as the labor measure, and capital stocks are the capital measure. This measure (MFP1) is comparable to the one used by BJ. MFP2 then adjusts MFP1 for differences in the average number of hours worked and for the composition of the labor force, as in Table 2. Average hours worked are lower than in the United States in many countries. In addition, the labor composition effect is smaller than one in all countries compared to the United States. As a result, MFP2 is lower than MFP1 for all countries but Hungary. Differences in labor input measures do not translate one to one to MFP, because they are weighted with the labor costs in value added, which is about two-thirds. Still, this can have a great impact: whereas Belgium has a productivity level of 87% of the United States according to MFP1, the level is 105% according to MFP2.

Instead of a GDP PPP, MFP alternative 3 is based on a value-added PPP. MFP3 levels are lower than MFP2 levels in almost all countries because VA PPPs are higher than GDP PPPs (see Table A.1). Although this is true for the market economy as a whole, this will not be the case for all detailed industries, as shown in Table 1. The final step toward our preferred MFP alternative is an adjustment for capital PPPs and composition, as shown in Table 3. Differences between capital stock and services input, weighted by the share of capital in value added (about one-third), account for the differences between MFP3 and MFP4. Because of lower levels of capital services per hour worked than capital stocks per hour worked relative to the United States, MFP4 levels are mostly higher than MFP3 levels.

For some countries, these adjustments almost cancel out: for Ireland both MFP1 and MFP4 are 99% of the United States and for Slovenia, MFP1 is 50% and MFP4 is 49% of the United States. However, for most countries the effect is substantial, between 5 and almost 20 percentage points. For example, Germany would appear to be 18 percentage points less productive than the United States according to the crudest productivity measure but only 7 percentage points according to the data-intensive measure. Furthermore, differences at the detailed industry level tend to be even larger; see Inklaar and Timmer (2008).

Irrespective of whether the differences are large or small, the main point is that our data-intensive measure does not suffer from the conceptual problems of cruder measures. Because output and input prices are industry-specific and the large heterogeneity in labor and capital inputs is recognized, we can have more faith in the results of studies based on these measures. This will be illustrated by a convergence analysis in the next section.

5. CONVERGENCE ANALYSIS

A key issue in modeling economic growth is whether there is a tendency of productivity levels to converge to a common level or whether differences in levels can continue indefinitely or even increase over time. BJ analyze this issue for a set of OECD countries for the period 1970–1987 and conclude that there are substantial differences in convergence patterns across sectors, with services showing convergence but no convergence in manufacturing. In this section we revisit their analysis, using more data-intensive productivity measures, and extend their findings from 1987 to 2005. For this we take our 1997 benchmark productivity

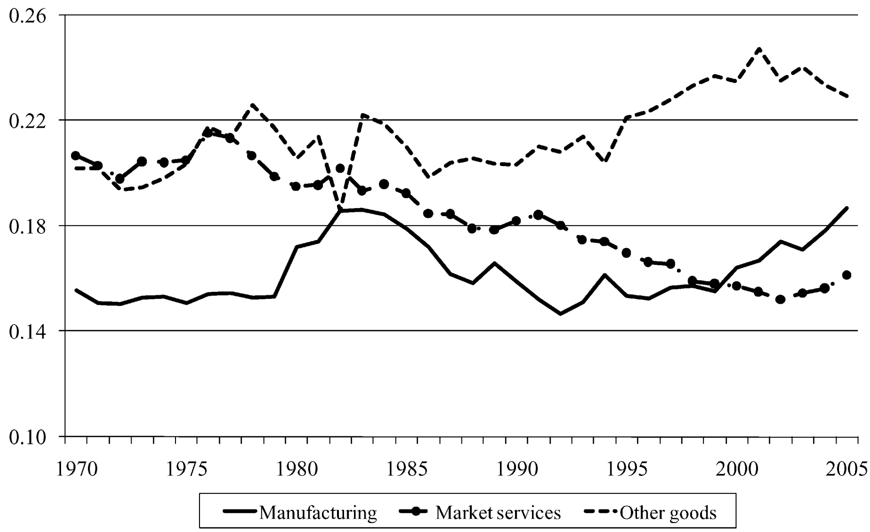

FIGURE 1. Standard deviation of productivity levels, 1970–2005.

levels and extrapolate them to 1970 and 2005 using relative MFP growth rates from the EU KLEMS database.[22,23]

As Islam (2003) argues in his survey, a test for productivity convergence should examine the dispersion of productivity levels over time (σ-convergence). A regression where productivity growth is explained by initial productivity levels can be used (β-convergence), but a significant coefficient on initial productivity levels is only a necessary, but not a sufficient condition for a smaller dispersion in productivity levels over time. Although β-convergence is useful in many economic models [e.g., Griffith et al. (2004)], we rely on σ-convergence in this paper.

Figure 1 shows the result of our industry group analysis for the period 1970–2005. The figure plots the standard deviation of productivity levels relative to the United States for three industry groups, namely manufacturing, market services, and other goods-producing industries. This last group includes agriculture, mining, utilities, and construction. Given the long time span, we were forced to reduce our sample to the thirteen countries with sufficient data.[24] Looking at the period 1970–1987 covered by BJ, their qualitative findings are confirmed: convergence in market services and no convergence in manufacturing and other goods-producing industries.[25] This pattern does not change in subsequent years: market services continue to show convergence, whereas the other two sectors even show some evidence of divergence since the mid-1990s. This contrasting convergence pattern across sectors confirms the key message of BJ, that an industry perspective is very important in the convergence debate.

This is further confirmed in Table 5, where we look at patterns of convergence in each of our 24 detailed industries. Data limitations require us to restrict the

TABLE 5. Standard deviation of industry productivity levels in 1980 and 2005 and a test for equality

	Group	1980	2005	Difference	T3-test
Agriculture, forestry, and fishing	OG	0.22	0.22	0.00	-0.06
Mining and quarrying	OG	1.00	0.58	-0.41	4.04*
Food and beverages	MFG	0.08	0.10	0.02	-0.73
Textiles, wearing apparel, and leather products	MFG	0.15	0.13	-0.02	0.81
Wood and wood products	MFG	0.23	0.24	0.02	-0.35
Paper, printing, and publishing	MFG	0.10	0.13	0.03	-2.19*
Coke, refined petroleum and nuclear fuel	MFG	0.20	0.21	0.02	-0.33
Chemicals and chemical products	MFG	0.16	0.19	0.03	n.a.
Rubber and plastics	MFG	0.36	0.36	0.00	-0.04
Nonmetallic mineral products	MFG	0.21	0.18	-0.03	0.87
Basic metals and fabricated metal products	MFG	0.20	0.15	-0.05	1.90*
Machinery	MFG	0.15	0.12	-0.02	0.80
Electrical and optical equipment	MFG	0.17	0.17	0.00	-0.05
Transport equipment	MFG	0.17	0.15	-0.01	0.78
Manufacturing, n.e.c.; recycling	MFG	0.42	0.27	-0.15	3.13*
Electricity, gas, and water supply	OG	0.12	0.12	0.00	0.02
Construction	OG	0.14	0.18	0.04	n.a.
Wholesale and retail trade	SER	0.36	0.23	-0.13	3.09*
Hotels and restaurants	SER	0.18	0.15	-0.03	1.16
Transport and storage	SER	0.27	0.27	-0.01	0.31
Post and telecommunications	SER	0.19	0.34	0.14	-2.02*
Financial intermediation	SER	0.19	0.23	0.05	-0.85
Business services	SER	0.14	0.12	-0.02	0.79
Social and personal services	SER	0.20	0.11	-0.09	4.14*

Notes: T3-test is a test for significant difference between standard deviations from Carree and Klomp (1997). This statistic asymptotically has a standard normal distribution. n.a. denotes that the test statistic could not be calculated due to specific parameter values; see Carree and Klomp (1997). Group denotes the industry group to which that industry belongs: OG: Other goods-producing, MFG: manufacturing, and SER: market services.

* Denotes a standard deviation in 2005 that is significantly different from that in 1980 at the 5%-level.

analysis to the period 1980–2005. Across industries, the evidence for convergence and divergence is also diverse: 13 industries have lower standard deviations in 2005 than in 1980, whereas 11 have higher standard deviations. The final column of Table 5 shows a test statistic for the equality of standard deviations from Carree and Klomp (1997).[26] Taking into account that the standard deviations over time are not independent, they formulate a test statistic that is asymptotically normally distributed. Five of the industries have a significantly positive test statistic, implying significant convergence, whereas two show significant divergence. Interestingly, two of the significantly converging industries are in manufacturing, which does not converge in the aggregate. Similarly, post and telecommunications, an industry in market services, is one of the industries showing significant divergence, whereas aggregate market services converge. In summary, the detailed industry perspective further reinforces the message of BJ that convergence patterns differ substantially across industries.[27]

6. CONCLUDING REMARKS

Economic growth analysis has been hampered by a lack of data of sufficient quality on industry productivity levels. Neoclassical production theory implies that accurate productivity-level estimates require industry-specific relative output and input prices and a thorough accounting for the heterogeneity of inputs.[28] Although each of these problems is widely acknowledged and has been partially addressed in various studies, this is the first study that provides a comprehensive treatment and does so at a detailed industry level.

As we have shown in our empirical results for twenty advanced OECD countries, the differences between crude and data-intensive measures are very important in practice: there are considerable differences across countries in average hours worked; the composition of the workforce in terms of educational attainment and experience; the use of ICT and non-ICT capital; and prices of industry output, intermediate inputs, and investment. Accounting for these differences has a substantial impact on productivity-level estimates. The new data-intensive measures provide a more reliable data set that can be used in a variety of studies on economic growth, structural change, and international trade.

In a convergence analysis, we confirm and strengthen the main conclusion from Bernard and Jones (1996) that convergence or divergence is an industry-specific phenomenon. Of the industry groups distinguished by Bernard and Jones (1996), only market services show convergence, whereas there is no convergence in manufacturing or other goods-producing industries. These findings hold for the period 1970–1987 as studied by Bernard and Jones (1996) but also extend to the more recent period 1987–2005 for a similar group of 13 advanced countries. At a more detailed industry level using data for 24 industries, we show even greater heterogeneity. Between 1980 and 2005, about half the industries show decreasing dispersion of productivity levels and the other half show *increasing* dispersion. There is no dominant convergence trend in sectoral productivity growth across advanced countries.

Our preferred data-intensive productivity-level estimates take into account many of the criticisms that have been raised against cruder estimates. However, this does not imply that all data issues are resolved. There are a number of areas for further improvement in the basic statistics underlying measurement of productivity growth and levels [Diewert (2008)]. Of particular importance are data on capital assets, such as land and inventories, which are not included in our set of assets due to missing data. More recently, attempts have been made to measure investment in intangible capital.[29] Some of the industry output prices, in particular for services industries such as finance and business services, are hard to measure, both over time and across countries.[30] More generally, it is true that more detailed measures of labor and capital are less reliable than more aggregate measures due to limited survey evidence, suggesting a trade-off between precision and measurement error.[31]

Notwithstanding these remaining issues, we would argue that our productivity-level estimates provide a fruitful starting point for further research. In our estimation, we have brought together different strands of the literature on topics such as PPPs and physical and human capital measurement, provided internationally comparable measures, and combined these in a coherent framework to show the importance of theory-based measurement. This should specifically open the door to examining the robustness of earlier findings in the literature to improvements in measurement practices [Hamermesh (2007)] and in general increase the degree of trust in cross-country growth analyses relying on industry productivity levels.

NOTES

1. See Islam (2003) and Barro and Sala-I-Martin (2004) for an overview.
2. See for example Keller (2002), Aghion and Howitt (2006), and Restuccia et al. (2008).
3. See also Harrigan (1999) and Caselli (2005).
4. Jorgenson and Yip (2001) provide relative MFP levels at the aggregate level for the G7 countries; see also Schreyer (2008). At the industry level, applications of this methodology to small sets of countries can be found in, for example, Jorgenson et al. (1987), van Ark and Pilat (1993), O'Mahony (1999), Lee and Tang (2000) and most recently Inklaar and Timmer (2007).
5. Level accounting is also known as development accounting [see, e.g., Caselli (2005)]. The methodology for level accounting is akin to the methodology for growth accounting. Instead of comparing two points in time, as in growth accounting, we compare two countries at a similar point in time. We stick to the name "level accounting" because it most clearly indicates the difference and similarity with growth accounting.
6. Comparisons of multifactor productivity can be made using the so-called primal and dual approaches. In the primal approach, relative MFP levels are based on comparisons of quantities, as here. Alternatively, in the dual approach, they are based on comparisons of prices. Usually, productivity measures are expressed in terms of relative quantities, as this is most closely related to the notion of production as a physical process in which quantities of inputs are converted into quantities of outputs. In theory, the two different estimates should be close, but in practice, this is not always the case, in particular when production structures differ considerably between the two countries being compared. We opt for the primal approach because we are interested in a full and consistent decomposition of output quantities, rather than output prices.
7. The GGDC productivity level accounts also provide gross output–based MFP levels, taking into account labor, capital, and intermediate inputs.
8. A subscript for time is left out to avoid notational cluttering in the level equations. All variables refer to the same year.
9. Bilateral comparisons do not satisfy transitivity. Alternatively, one can use the multilateral approach advocated by Caves et al. (1982a), who derive translog multilateral productivity indices that satisfy the transitivity requirement. The main reason not to opt for a multilateral approach is that this approach does not provide a consistent decomposition of relative output in terms of relative inputs and MFP levels. This is an important disadvantage given our interest in such decompositions.
10. Note that because of our ex ante approach to capital measurement, capital compensation V in this formula is based on ex ante measures of rates of return and will differ from the ex post measure of capital compensation used as a weight in equation (2). This is the so-called hybrid approach; see Oulton (2007) and Inklaar and Timmer (2008) for further discussion.
11. We aggregate over prices rather than over quantities because variation in prices across countries is much less than variation in quantities [see also Allen and Diewert (1981)].
12. See Inklaar and Timmer (2008) for more details.

13. The summation of capital compensation over all assets will typically differ from the capital compensation as given in the national accounts. The latter is used in the calculation of MFP; see note 8.

14. The expenditure approach to sectoral PPPs was pioneered by Jorgenson et al. (1987) and has most recently been applied by Biesebroeck (2007) and Sørensen and Schjerning (2009). The production approach based on producer unit values has been popularized by van Ark and Pilat (1993) and is explained in detail, with recent advances, in van Ark and Timmer (2001).

15. Refer to Timmer et al. (2007) for further details about the construction and data sources underlying these PPPs.

16. Subscripts to indicate this have been dropped to avoid cluttering.

17. See Table 5 for definitions of these sectors.

18. Sectoral value-added PPPs are generally higher than GDP PPPs, so most ratios in Table 1 are bigger than one. This is mainly because the latter includes nonmarket services that, according to the OECD results, are expensive in the United States compared to other countries.

19. Absolute log differences.

20. What is measured is actual hours worked, not hours paid, so it takes differences in the number of vacation days, sick days, etc. into account.

21. This broadly corresponds to workers with a tertiary education, such as a bachelor's degree or higher.

22. For the period 1970–1979, we partly rely on educational attainment data from de la Fuente and Doménech (2006) to estimate labor composition change.

23. By construction, our productivity levels pass the Sørensen (2001) test because we account for sectoral differences in output and input prices, both across countries and over time.

24. These are Australia, Austria, Belgium, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, Spain, the United Kingdom, and the United States.

25. BJ split up other goods-producing industries into agriculture, mining, utilities, and construction, and find convergence in agriculture and utilities but no convergence in mining and construction. For a comparison at this level of detail, see Table 5.

26. Tests for differences in standard deviations at the industry group level from Figure 1 show no significant changes over the 1970–2005 period.

27. Using PPPs based on expenditure prices only, Biesebroeck (2007) arrives at the same conclusion.

28. See Jorgenson and Griliches (1967), Diewert (1976), Caveset al. (1982b), Diewert and Morrison (1986), and studies in Jorgenson (1995a, 1995b).

29. See, for example, Basuet al. (2003) and Corrado et al. (2005).

30. See, for example, Abraham (2005).

31. Inklaar and Timmer (2009) find that although measurement error is higher for detailed measures, this is outweighed by the improvements in precision of the estimates in cross-country studies.

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APPENDIX

TABLE A.1. Various alternative measures of output PPPs

	GDP (OECD)	Value-added PPPs: Market economy	Manu-facturing	Other goods	Market services	Exchange rate
Australia	1.32	1.44	1.88	0.99	1.48	1.35
Austria	0.92	1.26	1.36	1.19	1.22	0.89
Belgium	0.91	1.06	0.94	1.26	1.06	0.89
Czech Republic	12.7	16.0	15.2	15.4	18.1	31.7
Denmark	8.43	9.07	11.16	11.22	7.81	6.60
Finland	1.00	1.02	1.01	0.85	1.08	0.87
France	0.97	1.18	1.07	1.48	1.13	0.89
Germany	0.99	1.08	1.05	1.52	1.01	0.89
Hungary	85.0	96.5	89.9	132.1	90.9	186.8
Ireland	0.85	0.99	1.13	1.17	0.94	0.84
Italy	0.82	0.96	0.70	1.02	1.07	0.88
Japan	168	229	166	366	230	121
Luxembourg	0.96	0.94	1.13	1.77	0.75	0.89
Netherlands	0.91	0.99	1.09	1.44	0.88	0.89
Portugal	0.67	0.75	0.91	0.82	0.68	0.87
Slovenia	0.46	0.59	0.53	0.69	0.62	0.67
Spain	0.72	0.86	0.87	0.93	0.84	0.88
Sweden	9.30	10.3	10.4	10.0	10.2	7.63
United Kingdom	0.63	0.75	0.74	0.85	0.71	0.61
United States	1.00	1.00	1.00	1.00	1.00	1.00

Source: GDP PPP and exchange rate from OECD (2002). Value-added PPPs based on the GGDC productivity level database [Inklaar and Timmer (2008)]. For countries that joined the euro in 1999, the 1999 conversion rate was used on the old pre-euro currencies. All in national currency per US$.